Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Induced Drag Estimation of Box Wings for Conceptual Aircraft Design

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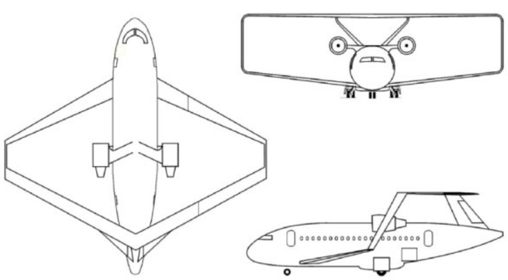

Dieter Scholz Hamburg University of Applied Sciences

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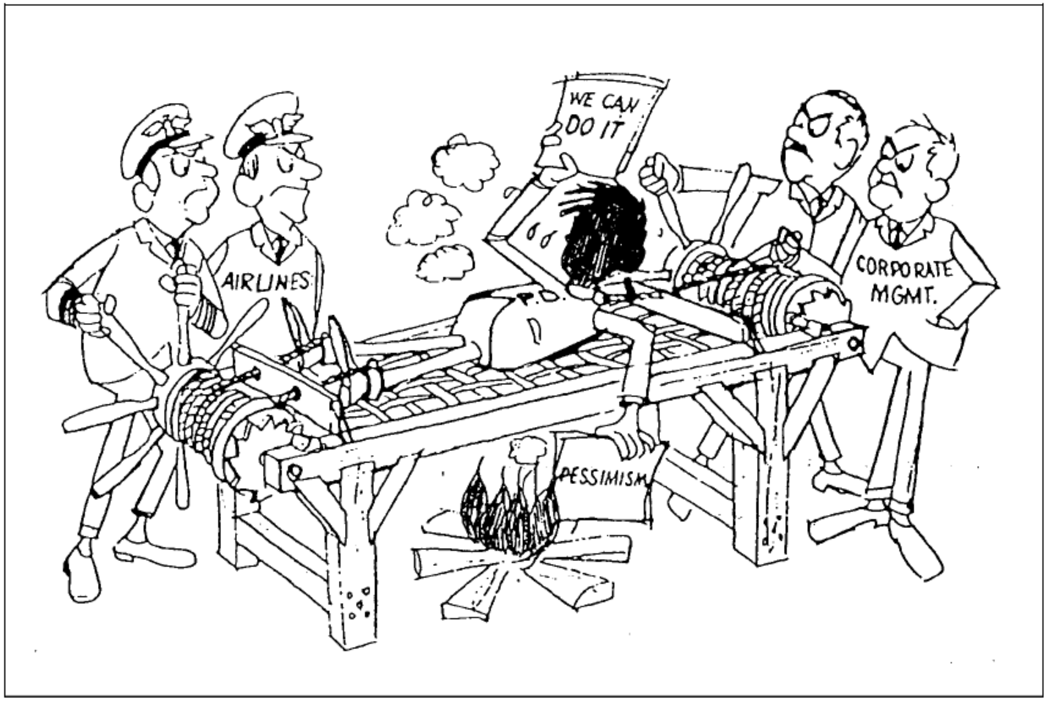
Explanations on the next pages

Conceptual Aircraft Design Characteristics

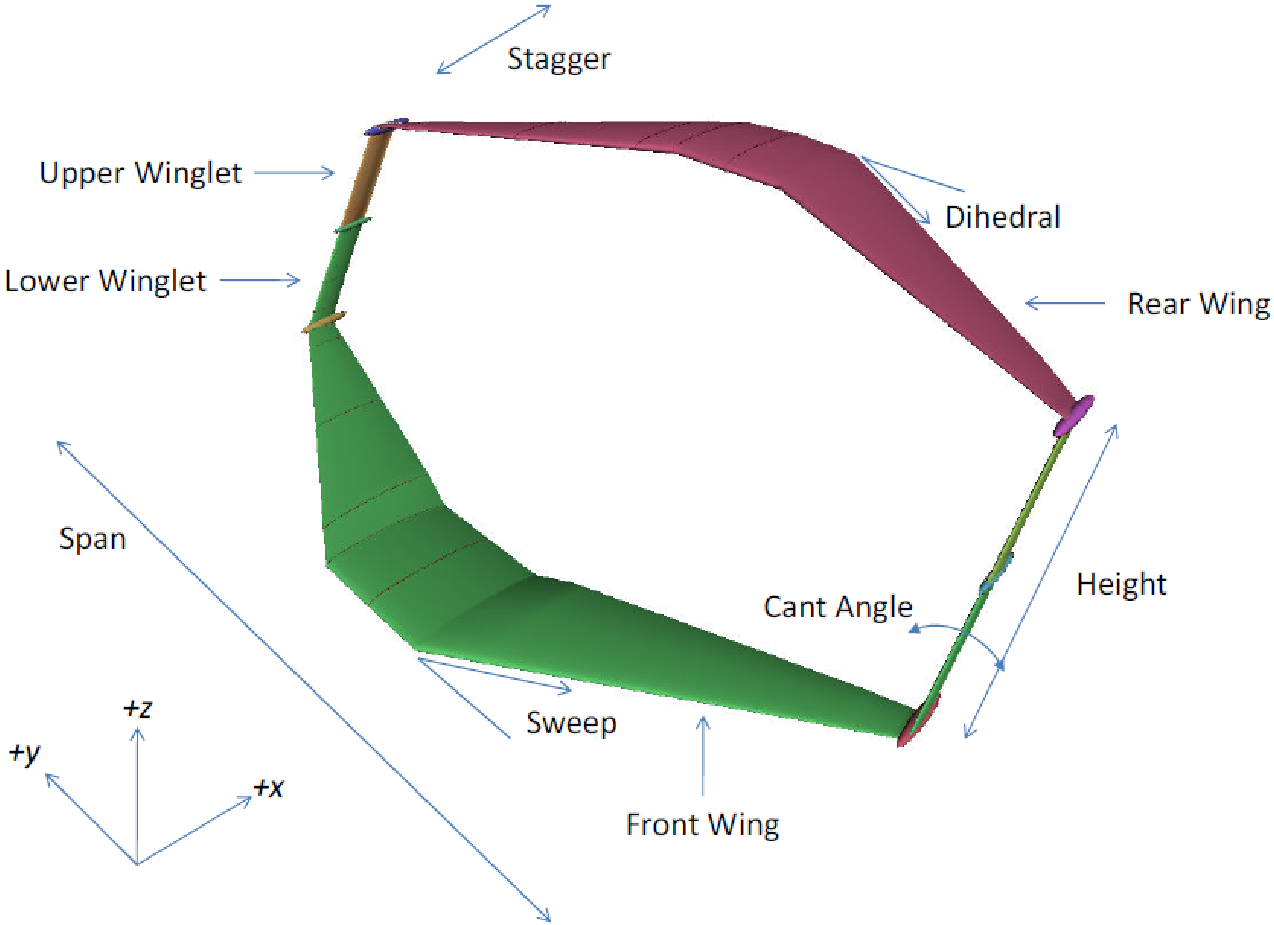
Early in the project:
Get reliable numbers with simple methods



"The design engineer is squeezed by the airlines into final performance guarantees which involve some risk and by his management to avoid that risk"

Scholz 1999

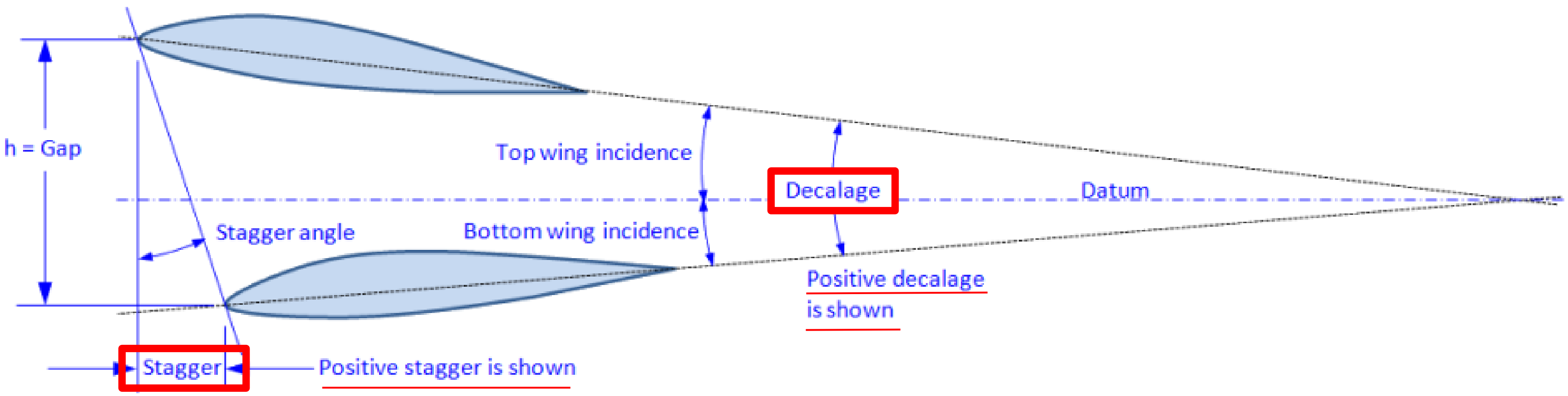
Box Wing



Khan 2010

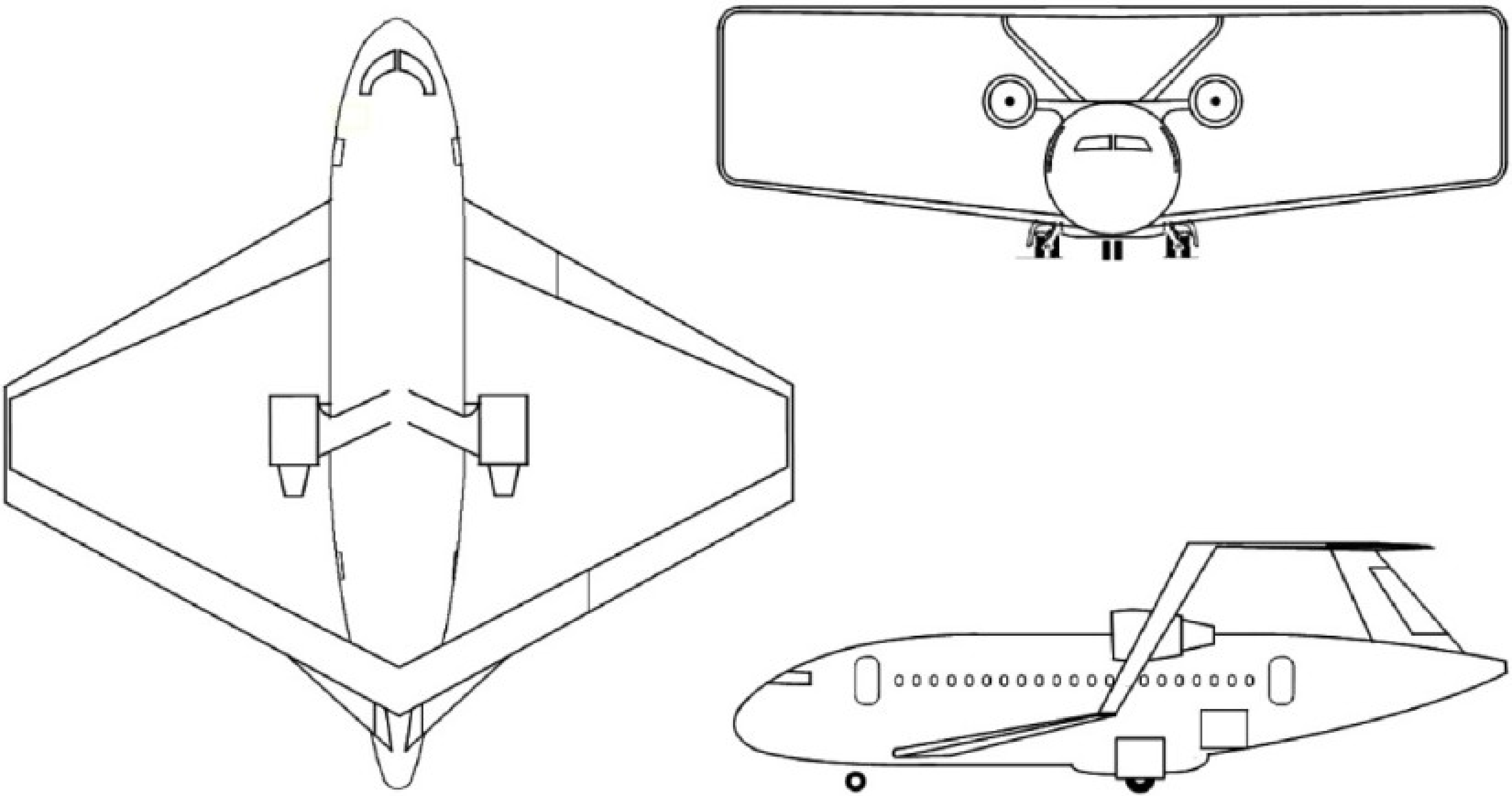
Introduction

Box Wing



Gudmundsson 2013

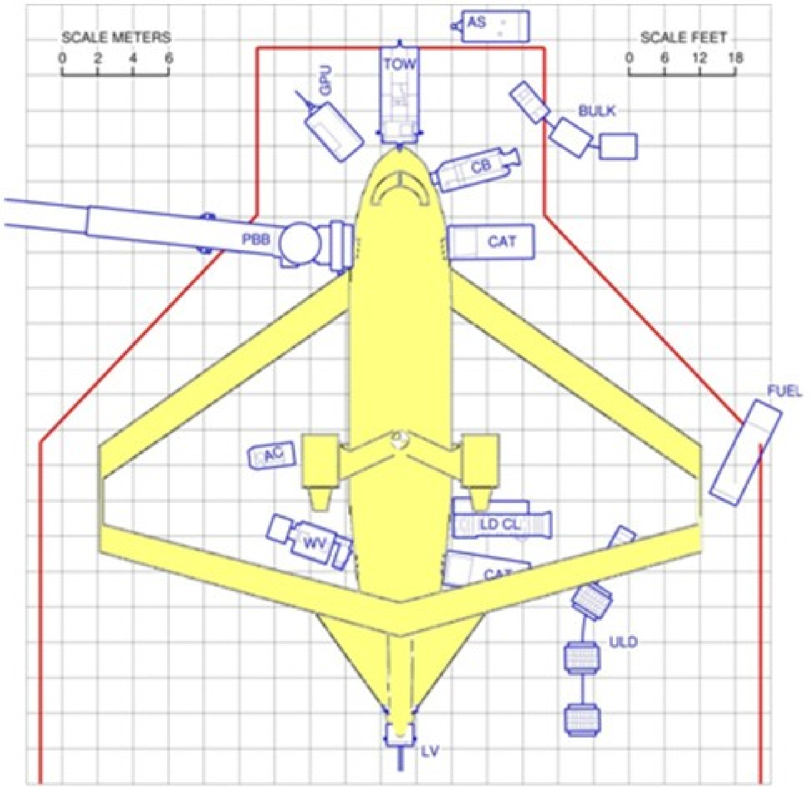
Box Wing Aircraft (BWA) Example



Scholz 2019

Introduction

Box Wing Aircraft (BWA) Example



Scholz 2019

Project "Airport 2030"

http://Airport2030.ProfScholz.de

Airport 2030 - Work Task 4.1
Evolutionary Aircraft Configurations
Possible A320 Successor

The project "Airport 2030" developed economic concepts and solutions for future air traffic demands. Hamburg University of Applied Sciences (HAW Hamburg) is working on efficient evolutionary aircraft configurations.

Scholz 2019

Project "Airport 2030" with Designs of Two Box Wing Aircraft

Scholz 2019

Video: Box Wing Aircraft in Flight

Model Editor: "Plane Maker"

Simulator: "X-Plane"

Aircraft flown by hand

Video
https://youtu.be/en65adjJpqk
on
http://youtube.ProfScholz.de

Scholz 2019

Induced Drag / Drag due to Lift

Airplane drag

zero-lift drag

drag due to lift

$$C_D = C_{D,0} + C_{D,i} = C_{D,0} + \frac{C_L^{\ 2}}{\pi A e} = C_{D,0} + \frac{C_L^{\ 2}}{\pi A}(1+\delta)$$

Oswald factor *e*

Induced Drag Calculation from Geometry

Calculate Oswald Factor *e* Without Input of *C_D0*

$$e = e_{theo} \cdot k_{e,F} \cdot k_{e,D_0} \cdot k_{e,M}$$

e	Oswald factor:
	correction factor for the aspect ratio to calculate drag due to lift
e_{theo}	theoretical Oswald factor, invisid drag due to lift only
$k_{e,F}$	correction factor: losses due to the fuselage
k_{e,D_0}	correction factor: viscous drag due to lift
$k_{e,M}$	correction factor: compressibility effects on induced drag

Nita 2012

Calculating parameters k_e,F, k_e,D0, k_e,M

$$e = e_{theo} \cdot k_{e,F} \cdot k_{e,D_0} \cdot k_{e,M}$$

Aircraft category	d_F / b	$k_{e,F}$	k_{e,D_0}
All	0.114	0.974	-
Jet	0.116	0.973	0.873
Business Jet	0.120	0.971	0.864
Turboprop	0.102	0.979	0.804
General Aviation	0.119	0.971	0.804

e_{theo} see next pages

$$k_{e,F} = 1 - 2\left(\frac{d_F}{b}\right)^2$$

$$k_{e,M} = a_e\left(\frac{M}{M_{comp}} - 1\right)^{b_e} + c_e$$

$a_e < 0; \quad c_e = 1$

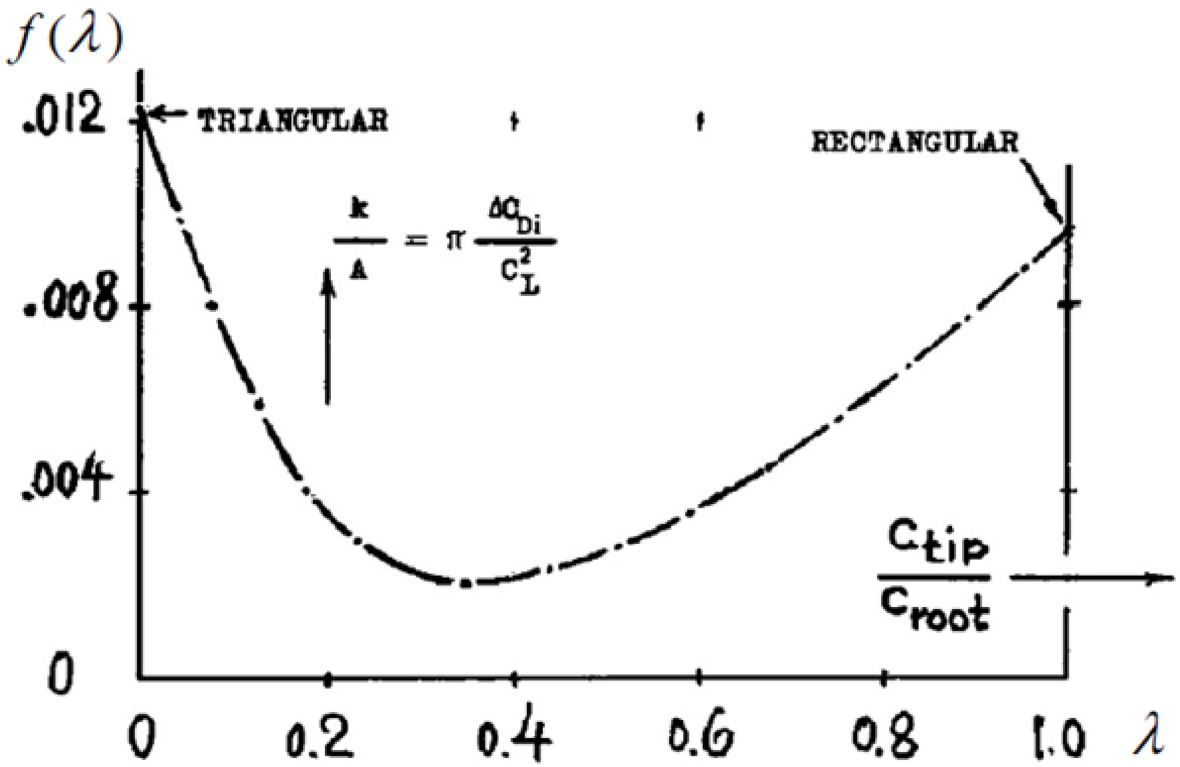
$$a_e = -0.00152$$
$$b_e = 10.82$$
$$c_e = 1$$
$$M_{comp} = 0.3$$

Parameters a_e and b_e are for cruise Mach number, M_{CR} around 0.8. For significant other M_{CR} see Scholz 2012.

Nita 2012

Calculating Parameter *e_theo*

Corrections to induced drag for unswept* wings as a function of taper ratio λ



$$f(\lambda) = k / A$$

$$C_{Di} = (1 + k)\, C_L^2 / \pi A$$

$$k = \delta$$

$$e_{theo} = \frac{1}{1+\delta}$$

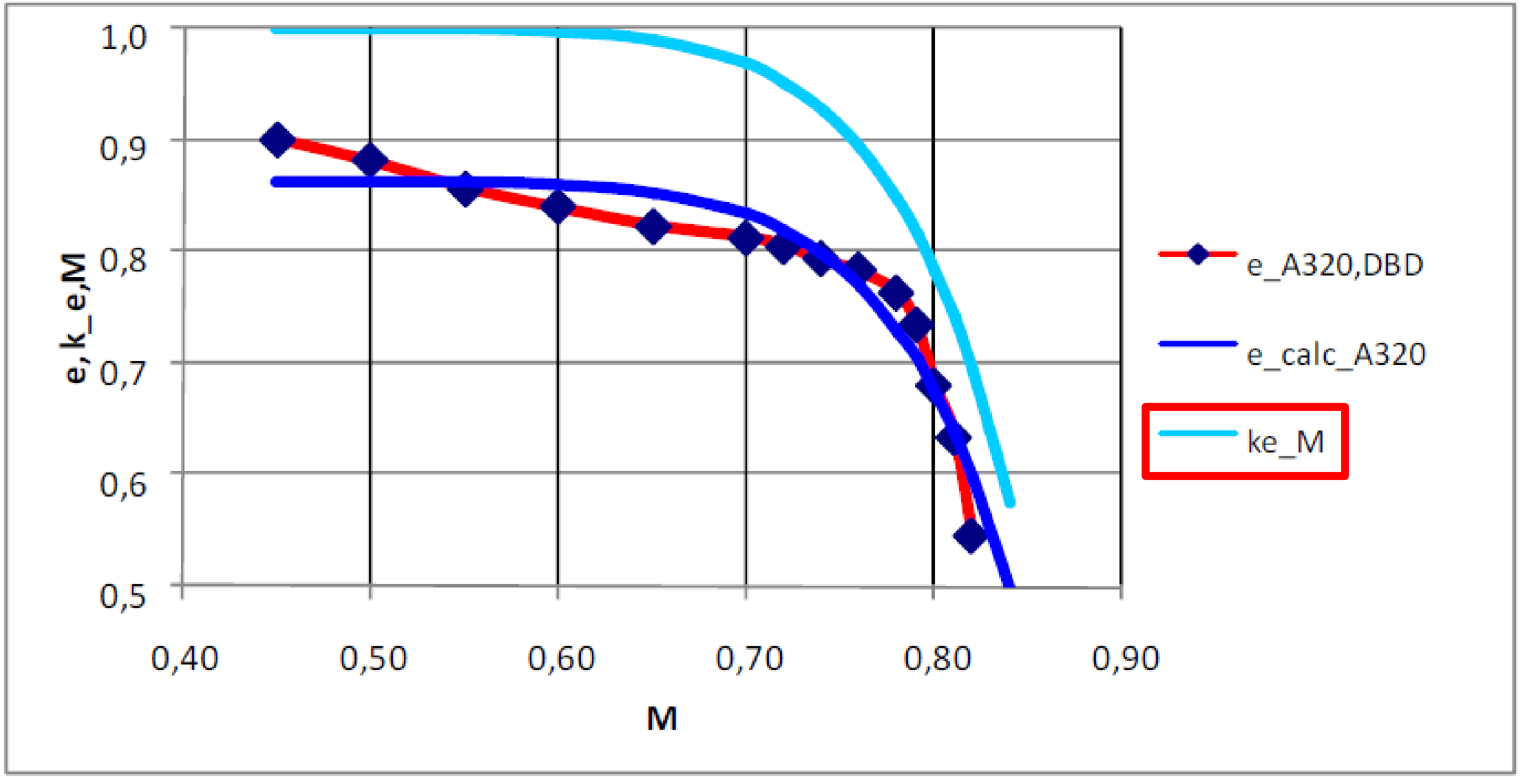
$$e_{theo} = \frac{1}{1 + f(\lambda) \cdot A}$$

* For swept wings see Nita 2012

Nita 2012

Induced Drag Calculation from Geometry

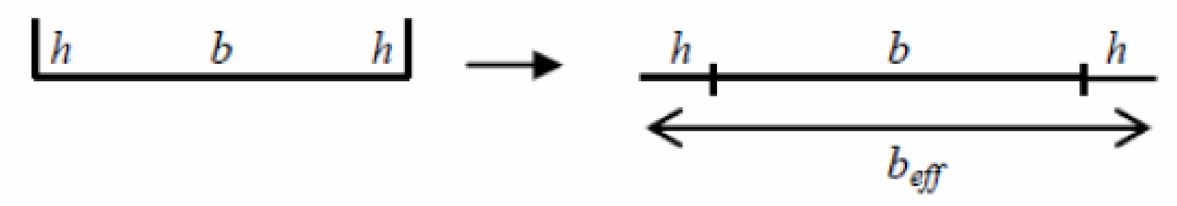
Influence of Mach Number Tuned to A320 Data: *k_e,M*



$k_{e,M}$ is calculated here with a_e = -0,00270 and b_e = 8,60 optimized for the A320.

Nita 2012

Estimating the Span Efficiency Factor for Non-Planar Configurations



The following relations can be derived from geometry:

$$\frac{b_{eff}}{b} = 1 + 2\frac{h}{b}$$

$$C_{D,i} = \frac{C_L^{\,2}}{\pi A e}$$

$$C_{D,i,WL} = \frac{C_L^{\,2}}{\pi A_{eff} e} = \frac{C_L^{\,2}}{\pi A e_{WL}}$$

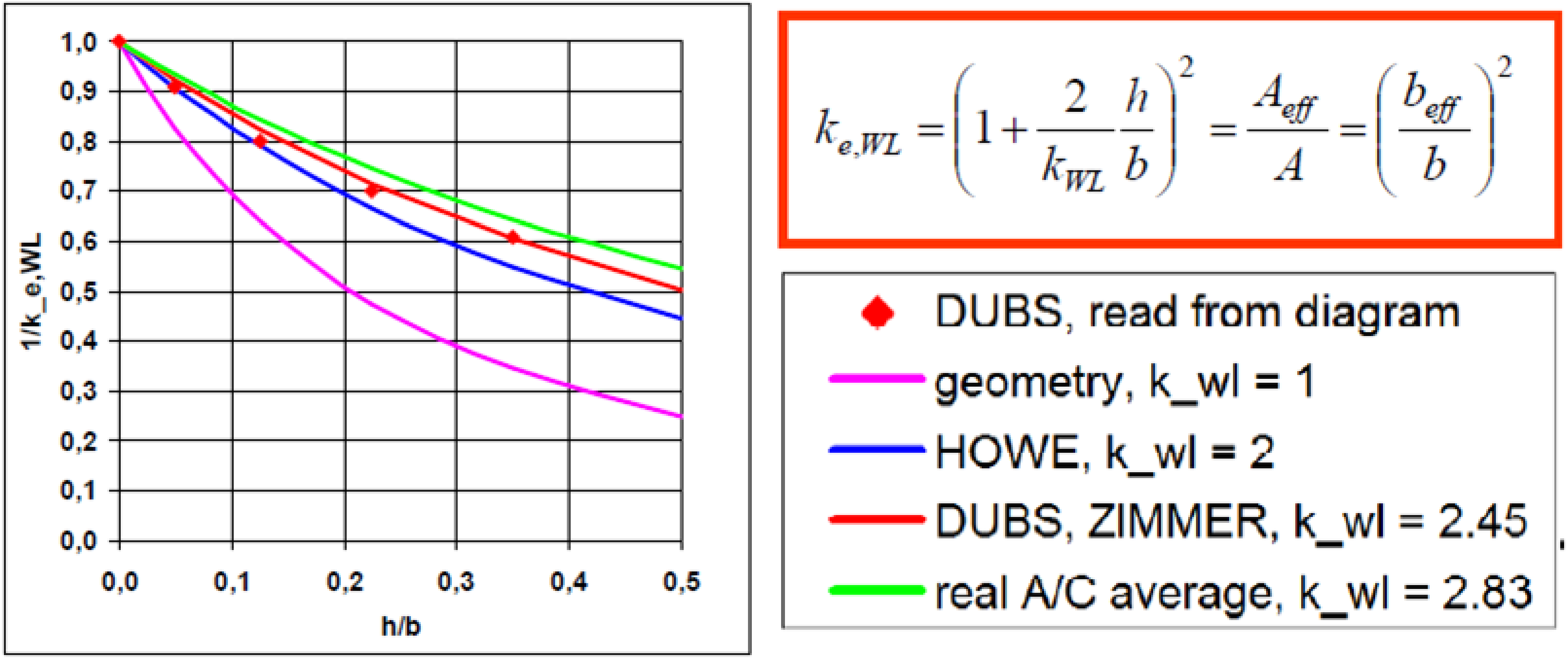
$$e_{WL} = \frac{A_{eff}}{A} \cdot e = \left(\frac{b_{eff}}{b}\right)^2 \cdot e \quad \rightarrow \quad e_{WL} = \left(1 + 2\frac{h}{b}\right)^2 \cdot e$$

Nita 2012

Induced Drag Calculation from Geometry

Correction of the Simple Geometrical Consideration via the Factor *k_WL*

$$e_{WL} = \left(1 + \frac{2}{k_{WL}} \frac{h}{b}\right)^2 \cdot e = k_{e,WL} \cdot e \; = \; e_{theo} \cdot k_{e,F} \cdot k_{e,D_0} \cdot k_{e,M} \cdot k_{e,WL}$$

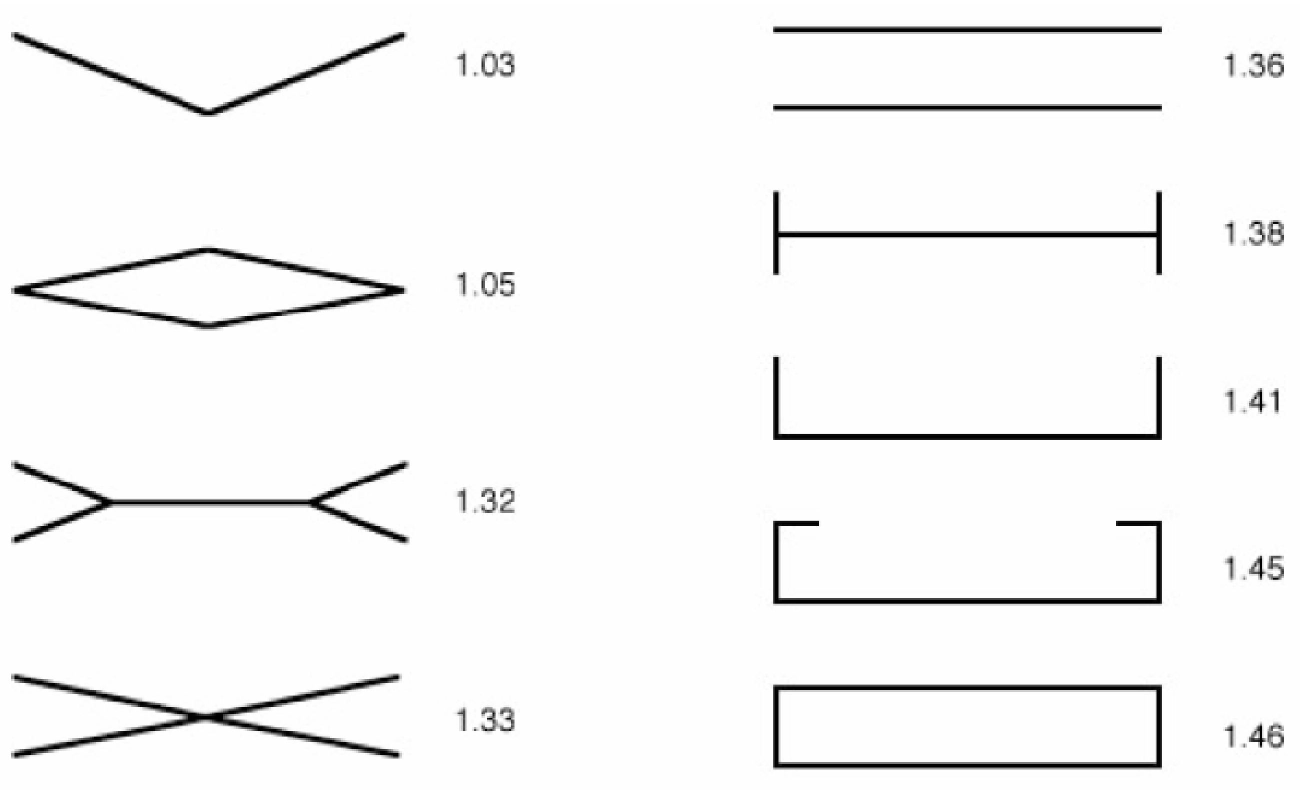


$$k_{e,WL} = \left(1 + \frac{2}{k_{WL}} \frac{h}{b}\right)^2 = \frac{A_{eff}}{A} = \left(\frac{b_{eff}}{b}\right)^2$$

Nita 2012

Induced Drag Calculation from Geometry

Relative Span Efficiency Factors *e_NP/e* for Wing Configurations Beyond Winglets



Span efficiency for various optimally loaded non-planar systems (h/b = 0.2)

Kroo 2005

Generalization of the Winglet Equation for Nonplanar Wings: *k_WL => k_NP*

The following relations can be written: (this time via a penalty factor called k_{NP}

$$e_{NP} = \left(1 + \frac{2}{k_{NP}} \frac{h}{b}\right)^2 \cdot e \Leftrightarrow e_{NP} = k_{e,NP} \cdot e$$

The factor for wings with winglets and dihedral, investigated above, becomes now a particular case of the factor k_{NP}.

Having the $k_{e,NP}$ from KROO, k_{NP} can be calculated for each configuration

$$k_{NP} = 2 \frac{h}{b} \cdot \frac{1}{\sqrt{k_{e,NP}} - 1}$$

Numbers on next page!

Nita 2012

Induced Drag Calculation from Geometry

Generalization of the Winglet Equation: Numbers for *k_NP*

$$e_{NP} = \left(1 + \frac{2}{k_{NP}}\frac{h}{b}\right)^2 \cdot e = k_{e,NP} \cdot e$$

$$= e_{theo} \cdot k_{e,F} \cdot k_{e,D_0} \cdot k_{e,M} \cdot k_{e,NP}$$

	h/*b* = 0.2	general
Non-planar configuration	$k_{e,NP}$	k_{NP}
	1.03	26.9
	1.05	16.2
	1.32	2.69
	1.33	2.61
	1.36	2.41
	1.38	2.29
	1.41	**2.13**
	1.45	1.96
	1.46	1.92

Nita 2012

An Equation with Another Structure for the Box Wing

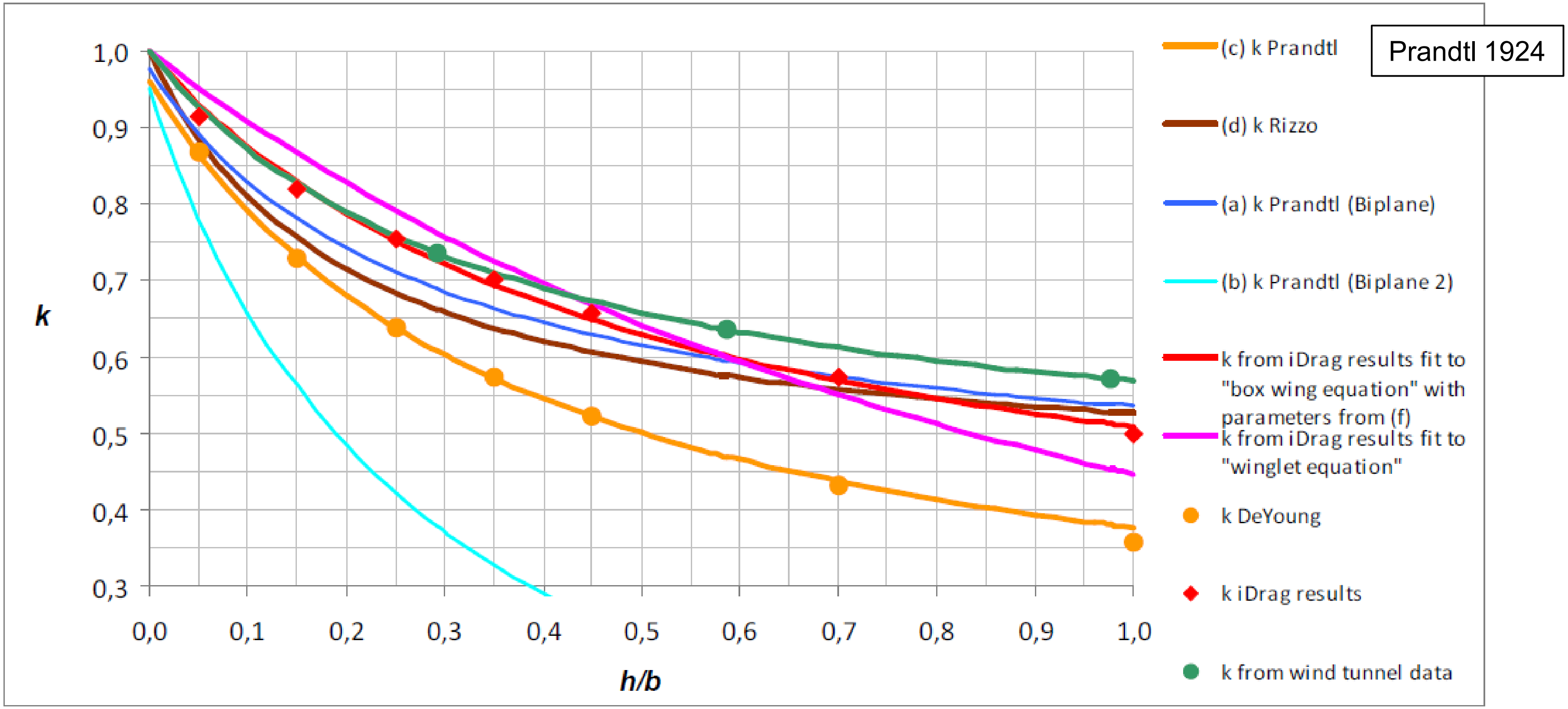
$$\frac{e_{NP}}{e} = k_{e,NP} = 1/k$$

$$\frac{D_{i,box}}{D_{i,ref}} = k = \frac{k_1 + k_2 \cdot h/b}{k_3 + k_4 \cdot h/b}$$

box wing equation

Induced Drag Calculation from Geometry

Initial Data Comparison from DLRK 2012 (Nita 2012)



DLRK 2012: Deutscher Luft- und Raumfahrtkongress (German Aerospace Congress), Berlin, 2012
Proceedings: http://www.dlrk2012.dglr.de/publikationen
Paper: https://nbn-resolving.org/urn:nbn:de:101:1-201212176728

Curve Fitting Results from DLRK 2012 (Nita 2012)

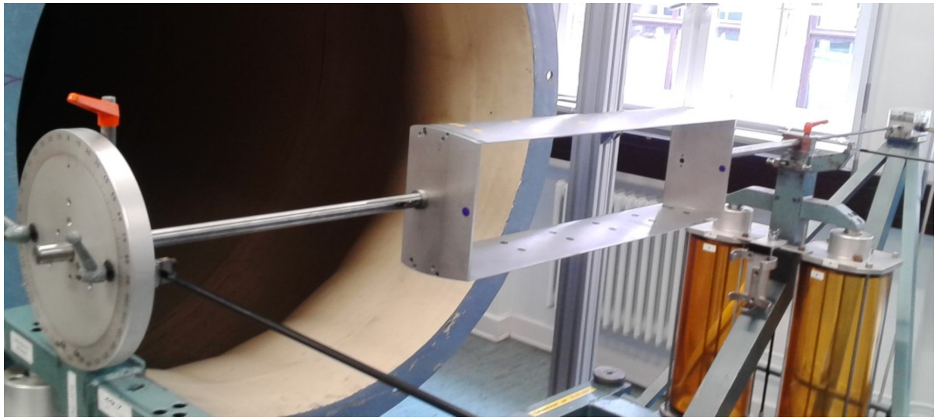
Case	Configuration	Author	k_1	k_2	k_3	k_4	k for $h/b \rightarrow 0$	k for $h/b \rightarrow \infty$
(a)	Biplane	Prandtl*	1	-0.66	2.1	7.4	0.976	-0.089
(b)	Biplane (2)	Prandtl	1	-0.66	1.05	3.7	0.952	-0.178
(c)	Box wing	Prandtl	1	0.45	1.04	2.81	0.962	0.160
(d)	Box wing	Rizzo	0.44	0.959	0.44	2.22	1	0.432
(e)	Box wing	iDrag best fit	1.304	0.372	1.353	1.988	0.964	0.187
(f)	Box wing	iDrag $k_1 = k_3$	**1.037**	**0.571**	**1.037**	**2.126**	**1**	**0.269**

* here, a different equation is used: $k = 0.5 + \dfrac{k_1 + k_2 \cdot h/b}{k_3 + k_4 \cdot h/b}$.

Subsequent additional wind tunnel measurements and calculation with VLM showed room for improvement !

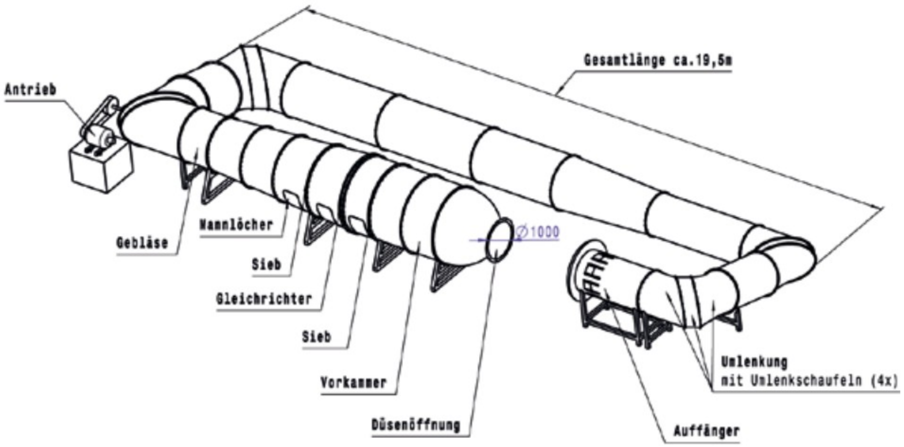
Wind Tunnel Measurements

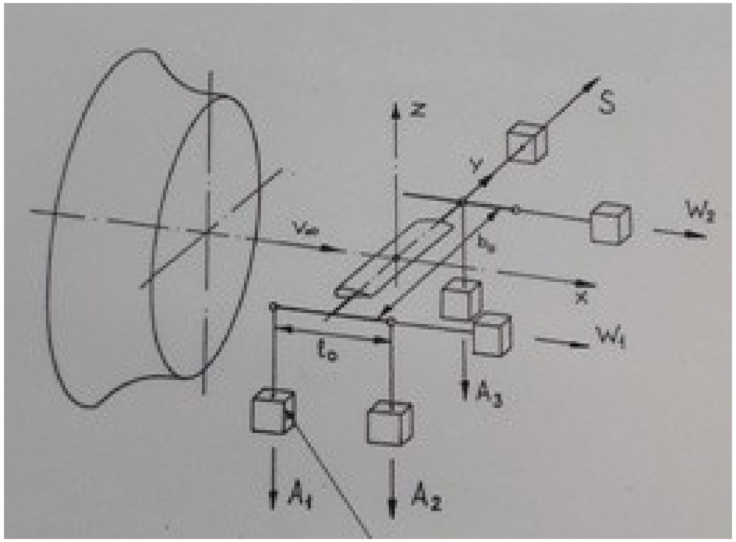
Wind Tunnel and Force Measurements



Wind tunnel with open test section (Göttingen-Type)

Chord, *c*: 100 mm
Reynoldsnumber, Re: 160000
Air speed ≈ 25 m/s



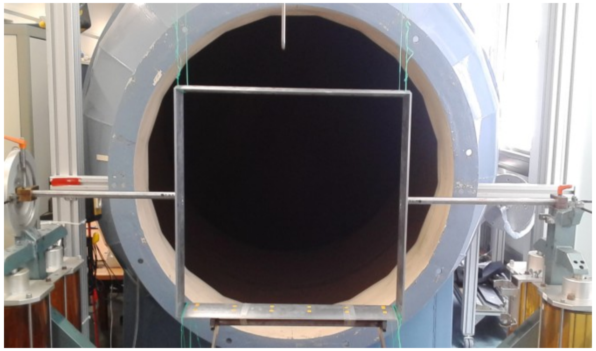


Wind Tunnel Measurements

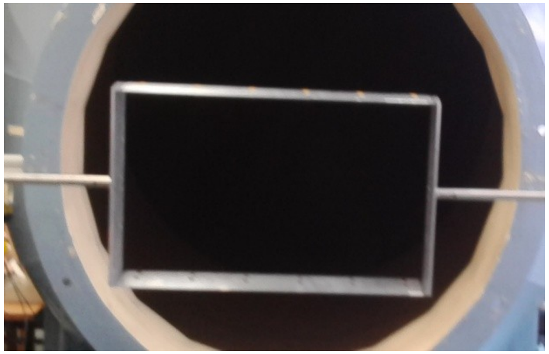
Box Wing Setup in the Wind Tunnel

Airfoil used: NACA0015

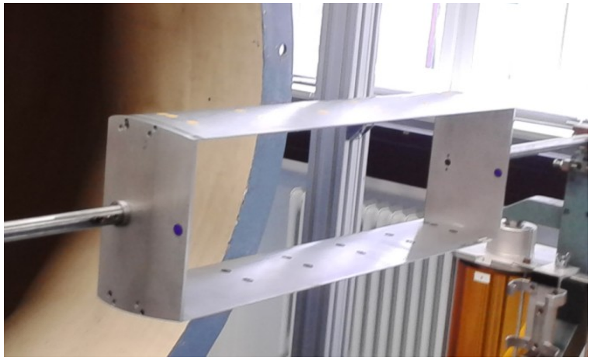
Reference wing:
span, *b*: 520 mm
chord, *c*: 100 mm
$A = b/c = b^2 / S = 5.2$



h/b = 0.93



h/b = 0.62

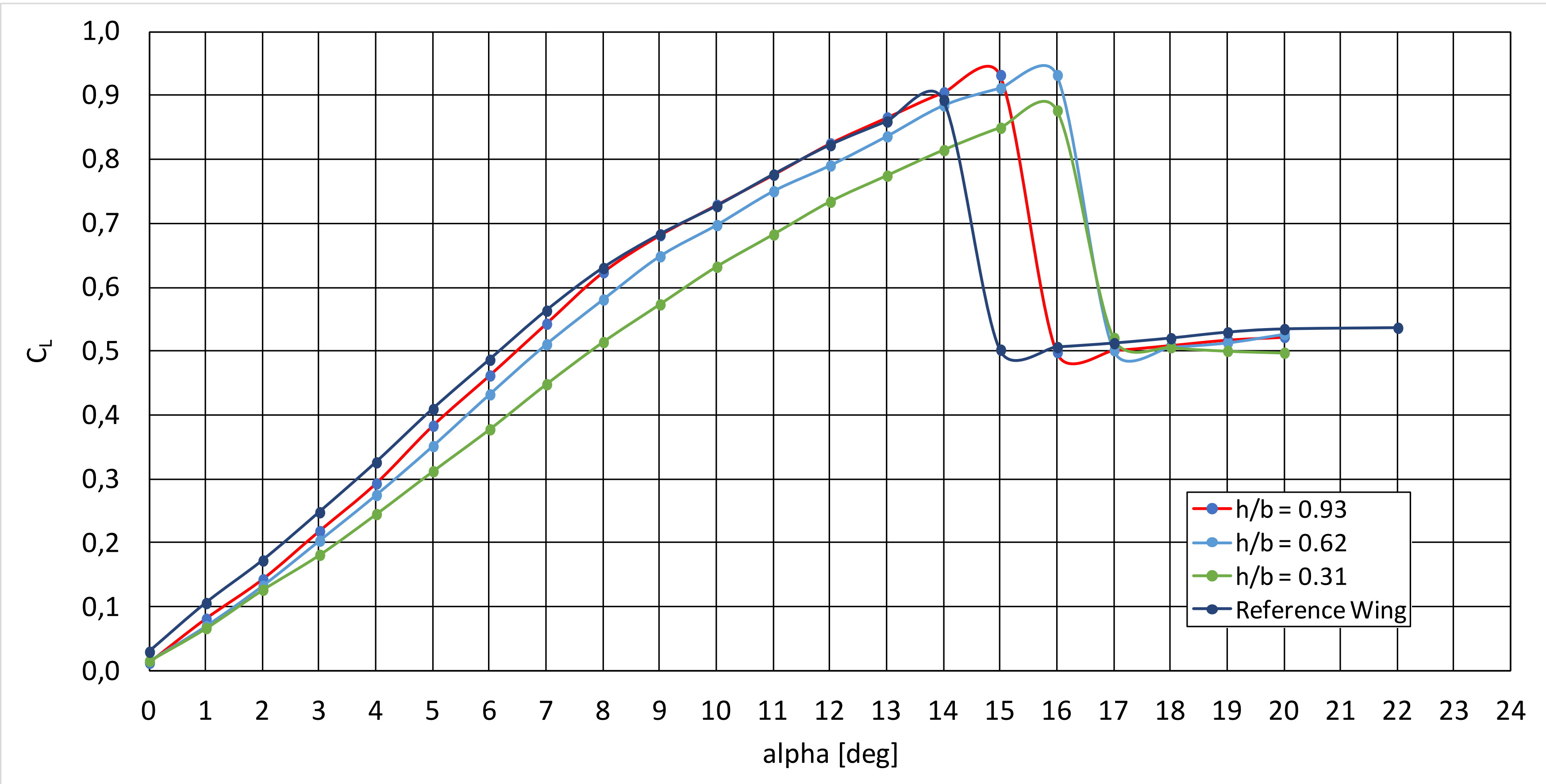


Box wings from
two reference wings:
$A = b^2 / S = 2.6$

hight (h) to span (b) ratio:
h/b = 0.31

Wind Tunnel Measurements

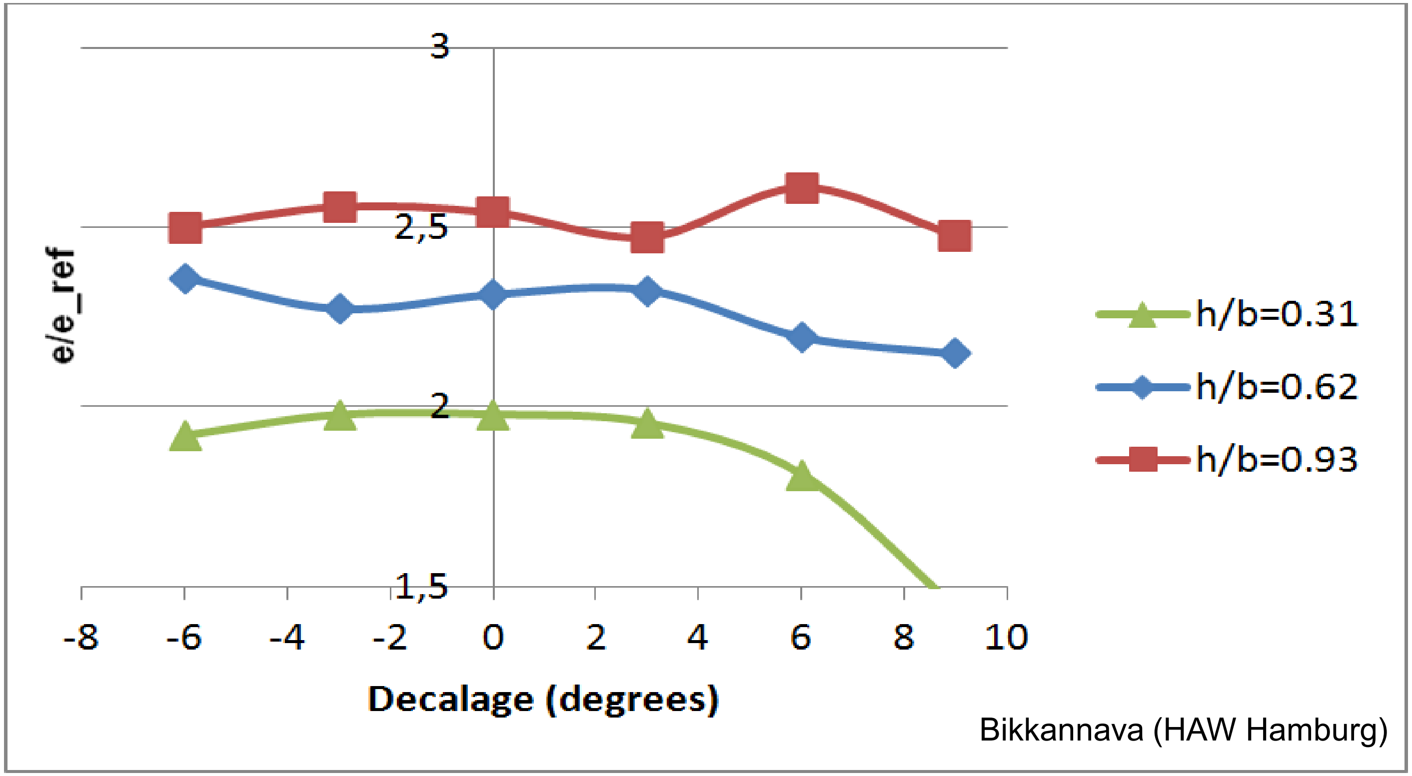
Box Wing *C_L = f(alpha)*

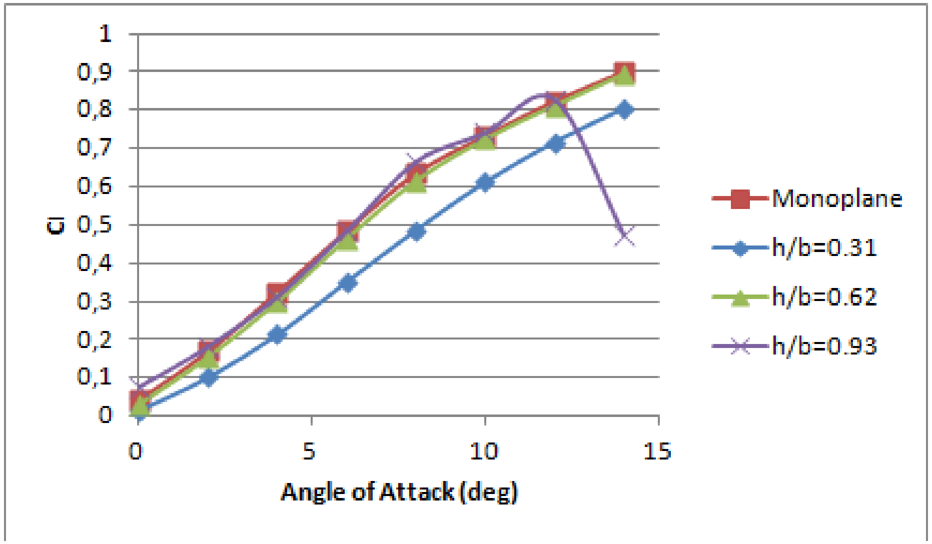


Ribeiro (HAW Hamburg)

Wind Tunnel Measurements

Decalage: No Systematic Advantage => Advice: Do Not Apply Decalage!

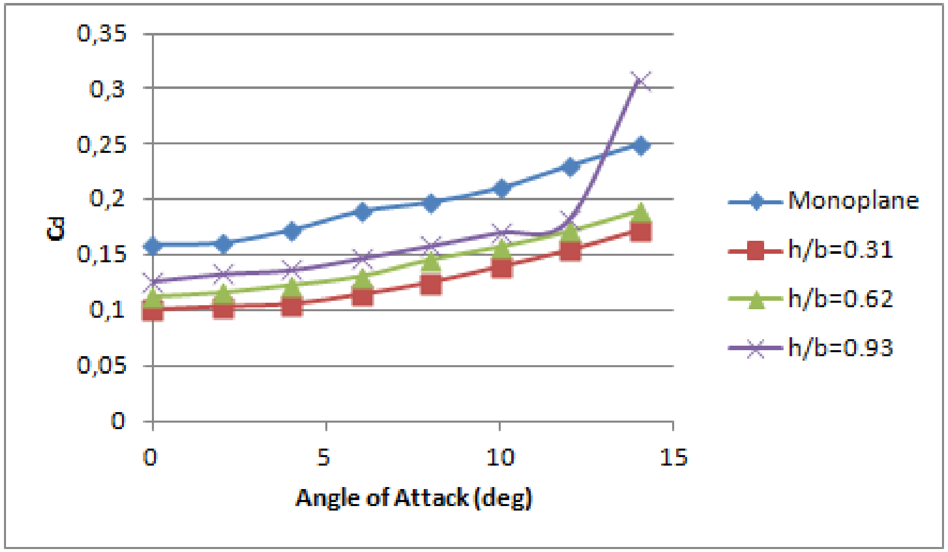




Lift Coefficient v/s AoA, no decalage

all h/b

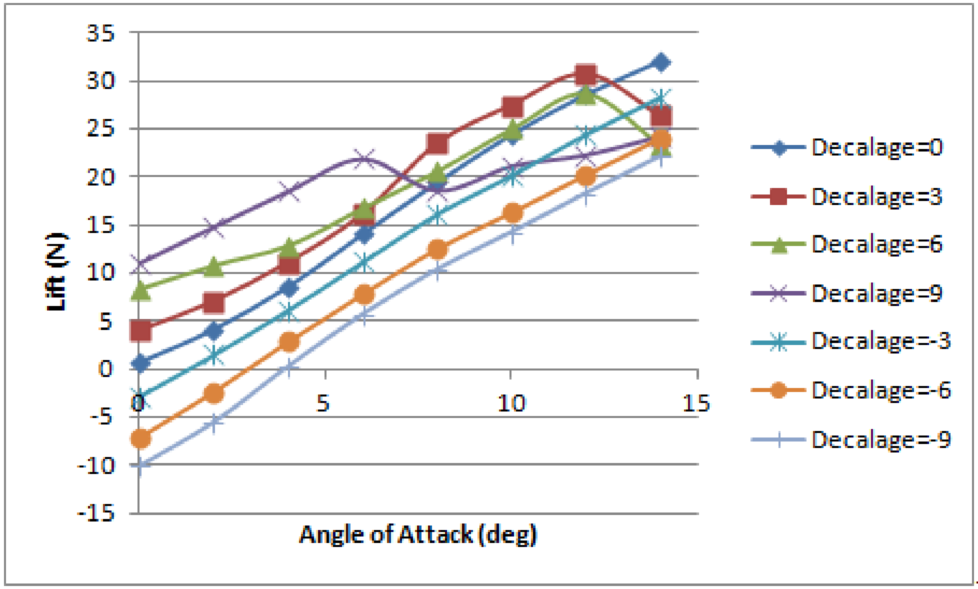
no decalage



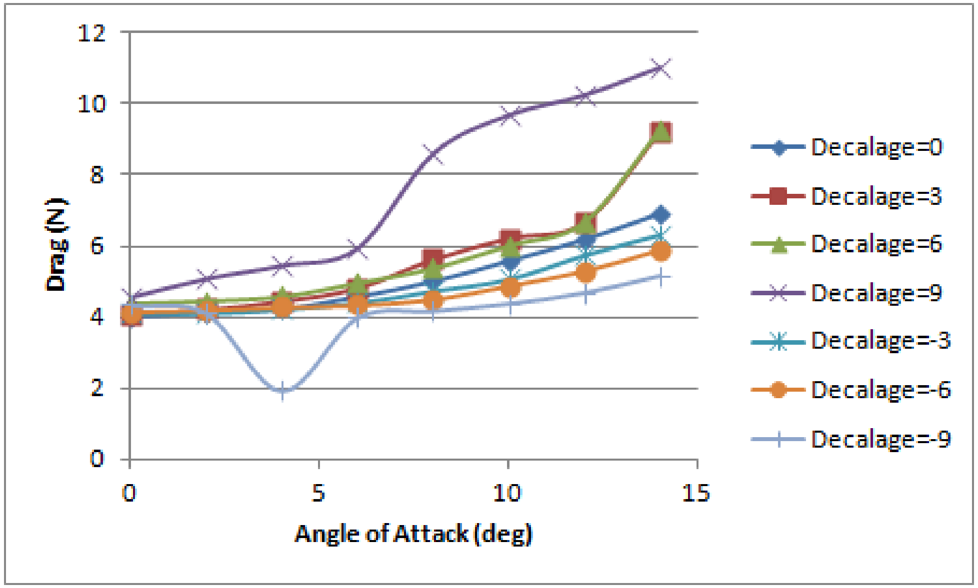
Drag Coefficient v/s AoA, no decalage

Absolute drag coefficient not representative !

Bikkannavar (HAW Hamburg)



h/b=0.31 Lift vs. AoA



h/b=0.31 Drag vs. AoA

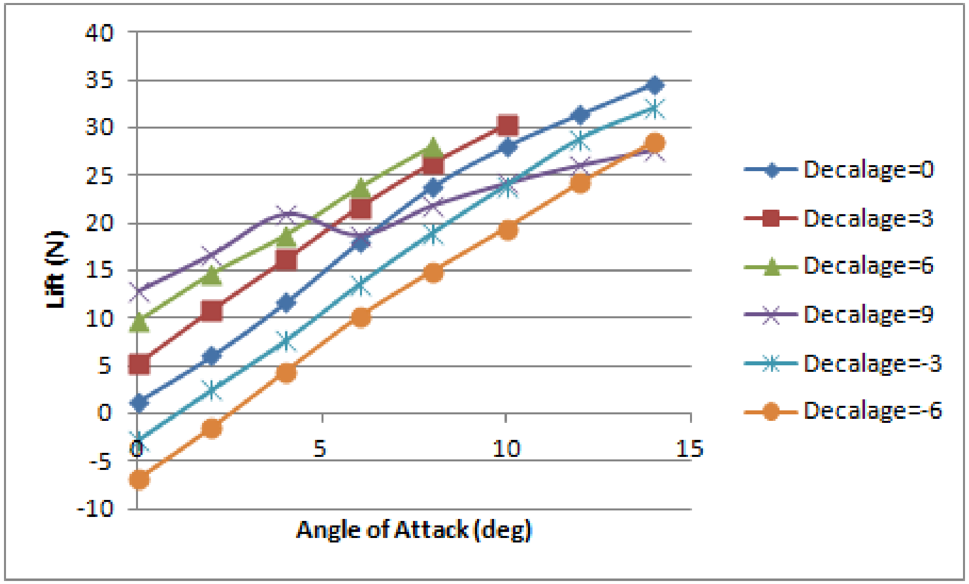
decalage

and

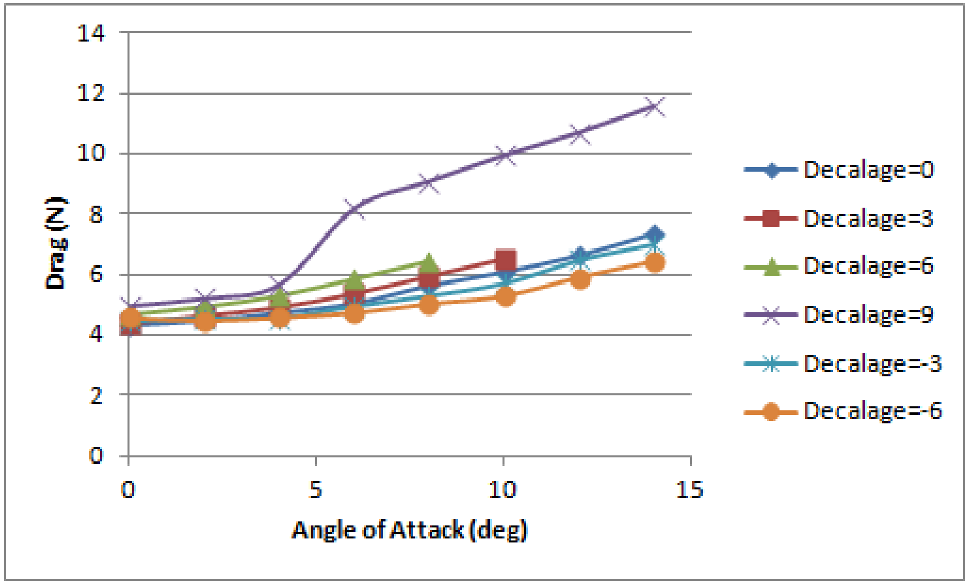
h/b = 0.31

Absolute drag not representative !

Bikkannavar (HAW Hamburg)



h/b=0.62 Lift vs. AoA



h/b=0.62 Drag vs. AoA

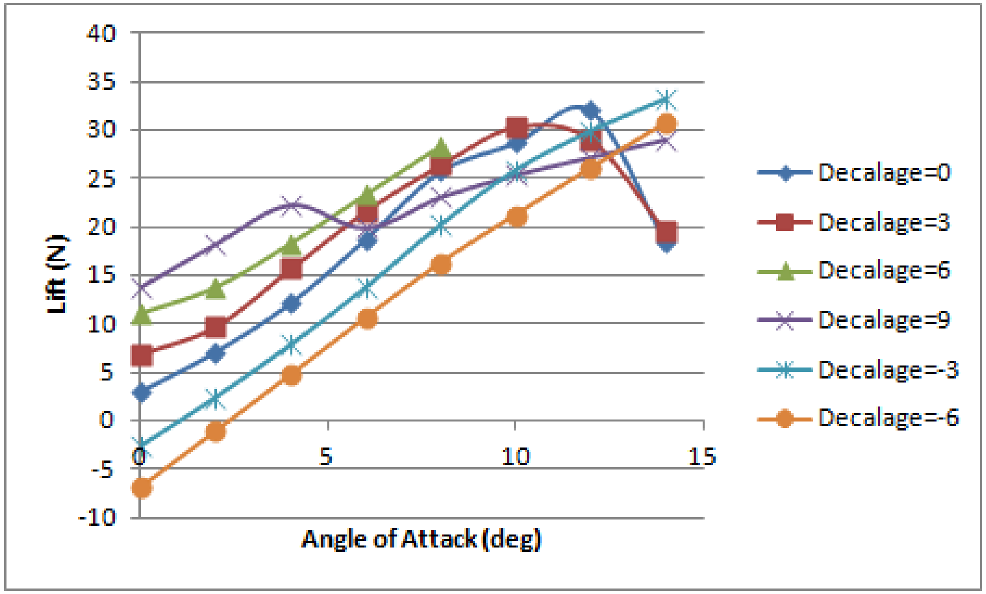
decalage

and

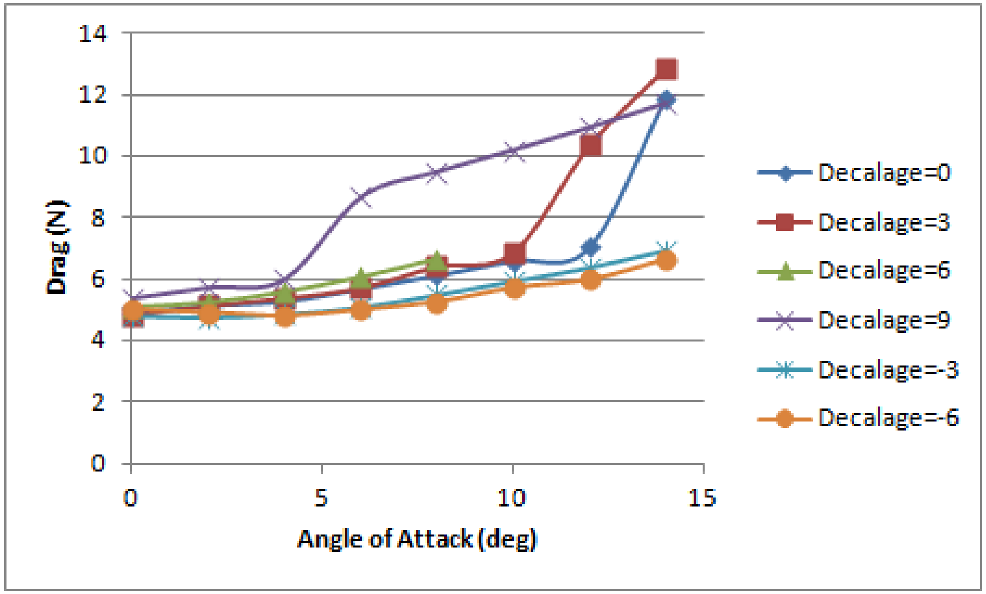
h/b = 0.62

Absolute drag not representative !

Bikkannavar (HAW Hamburg)



h/b=0.93 Lift vs. AoA



h/b=0.93 Drag vs. AoA

decalage

and

h/b = 0.93

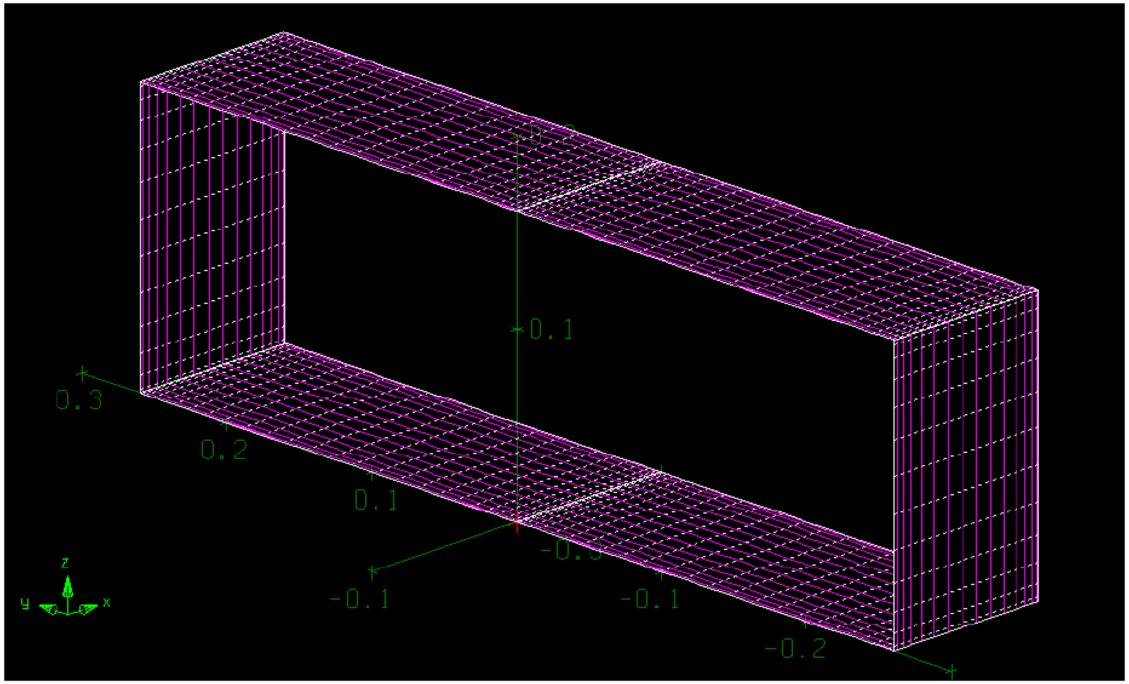
Absolute drag not representative !

Bikkannavar (HAW Hamburg)

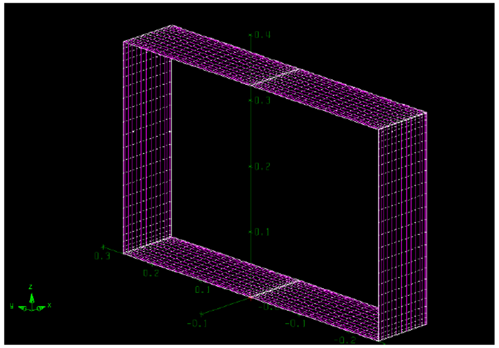
Vortex Lattice Method (VLM)
and
Comparison with Measurements

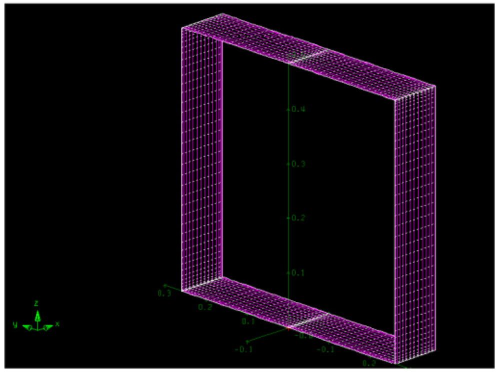
Vortex Lattice Method

Athena Vortex Lattice (AVL)



h/b = 0.31





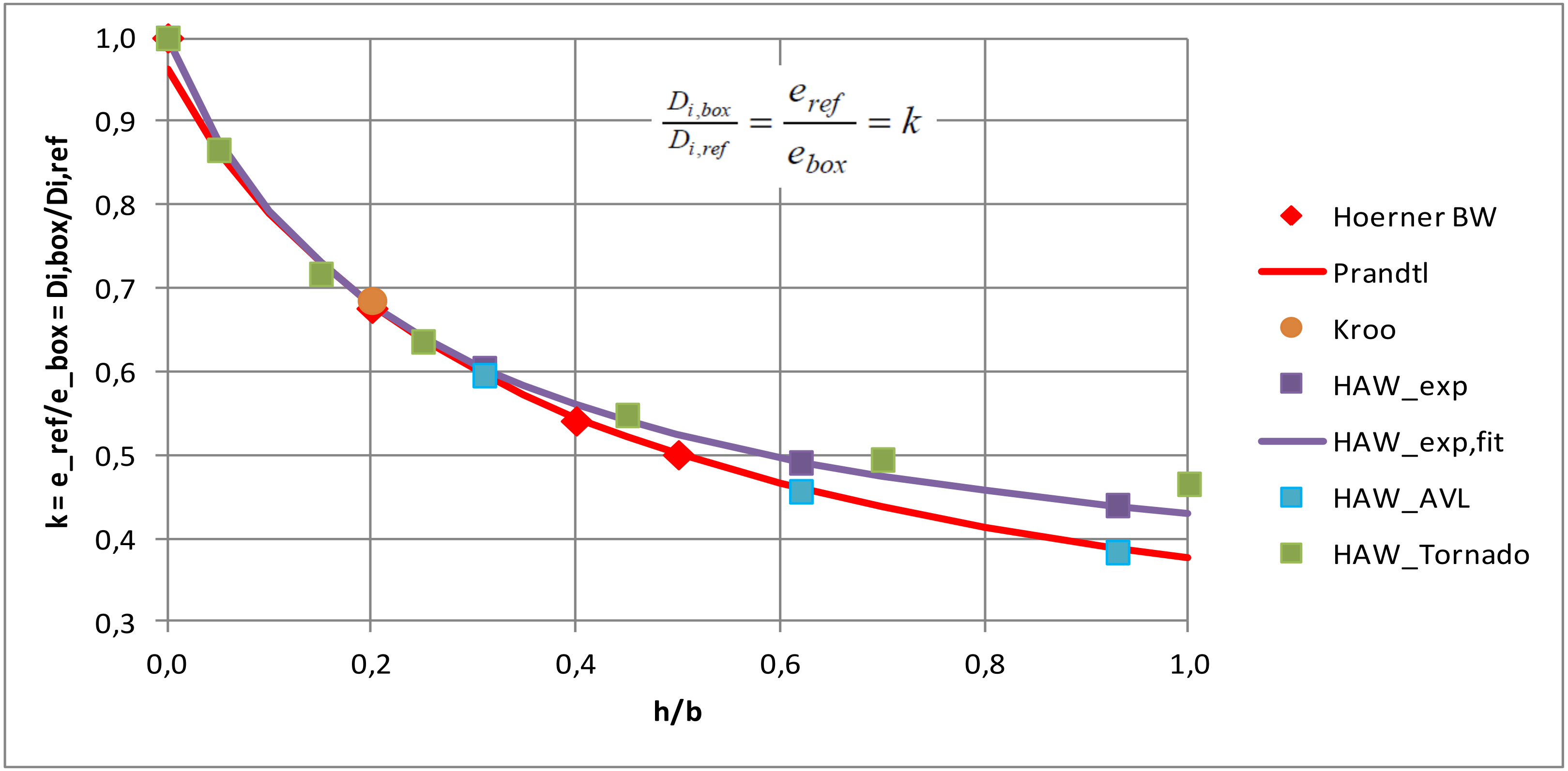
h/b = 0.62

h/b = 0.93

Ribeiro (HAW Hamburg)

Comparison: Literature, Wind Tunnel, VLM

Final Result for Box Wing Induced Drag



HAW_exp:	Similar wind tunnel measurements by Fekete, Bikkannavar, Ribeiro. Averaged values.
HAW_AVL:	Ribeiro (HAW Hamburg) using AVL
HAW_Tornado:	Caja Calleja (HAW Hamburg) using Tornado

Comparison: Literature, Wind Tunnel, VLM

Fitting the Wind Tunnel Measurements –

Proposed Equation to Calculate Induced Drag of Box Wings in Conceptual Aircraft Design

$$\frac{D_{i,box}}{D_{i,ref}} = k = \frac{k_1 + k_2 \cdot h/b}{k_3 + k_4 \cdot h/b}$$

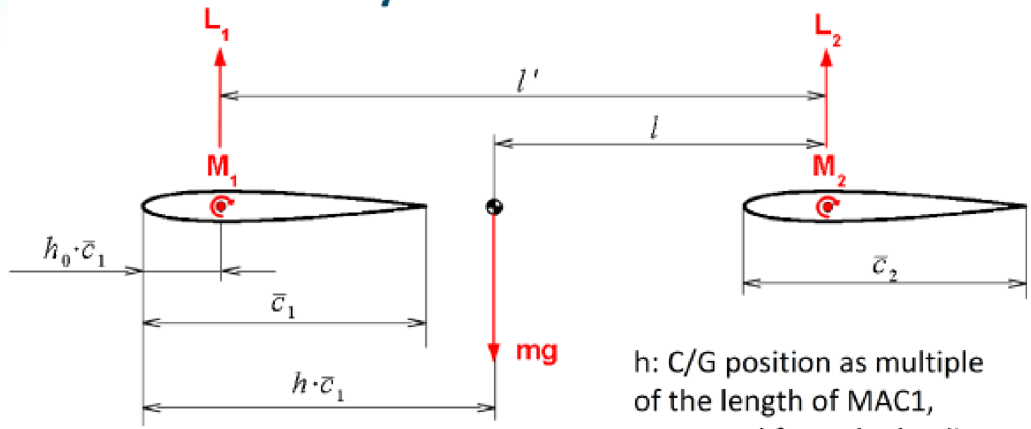
box wing equation

$k_1 = k_3$:	0,6952	
k_2:	0,8350	
k_4:	2,8569	
$h/b \rightarrow$ infinity:		$k_2 / k_4 = 0{,}2923$
$h/b = 0$:		1,0000

- Results from three similar wind tunnel measurement campaigns by Fekete, Bikkannavar, and Ribeiro at HAW Hamburg were averaged.
- Calculations with two VLM – AVL and Tornado – confirmed the measurements.
- **Wind tunnel measurements were fitted to the "box wing equation" (purple curve on previous page) with k-values as given here.**
- The box wing equation compares a box wing and a reference wing with the same aspect ratio $A = b^2/S$, where S is the total wing area.
- The box wing equation was prepared for rectangular and unswept wings.

Induced Drag with Unequal Lift Share

Box Wing Aircraft: Longitudinal Static Stability



h: C/G position as multiple of the length of MAC1, measured from the leading edge of MAC1

Stability Limit

$$h < h_0 + \boxed{\frac{dC_{L,2}}{dC_L} \cdot \overline{V}' \frac{\bar{c}}{\bar{c}_1}}$$

→ needs to be as high as possible

SCHIKTANZ, D.; SCHOLZ, D.: The Conflict of Aerodynamic Efficiency and Static Longitudinal Stability of Box Wing Aircraft. Venice, CEAS 2011

Schiktanz 2011

Control Limit → $C_{L,2}$ needs to be low. Thus for a given C_L $C_{L,1}$ needs to be increased

Trim Condition → $C_{L,2}$ needs to be lower than $C_{L,1}$ => $C_{L,1} / C_{L,2} > 1$

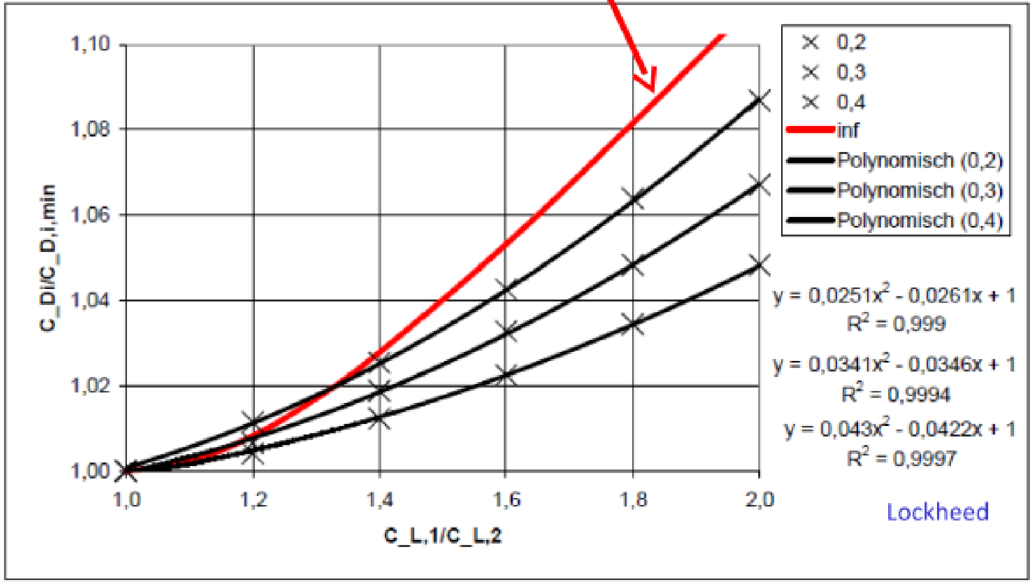
Forward wing needs higher lift coefficient than aft wing

Munk: drag independant of stagger

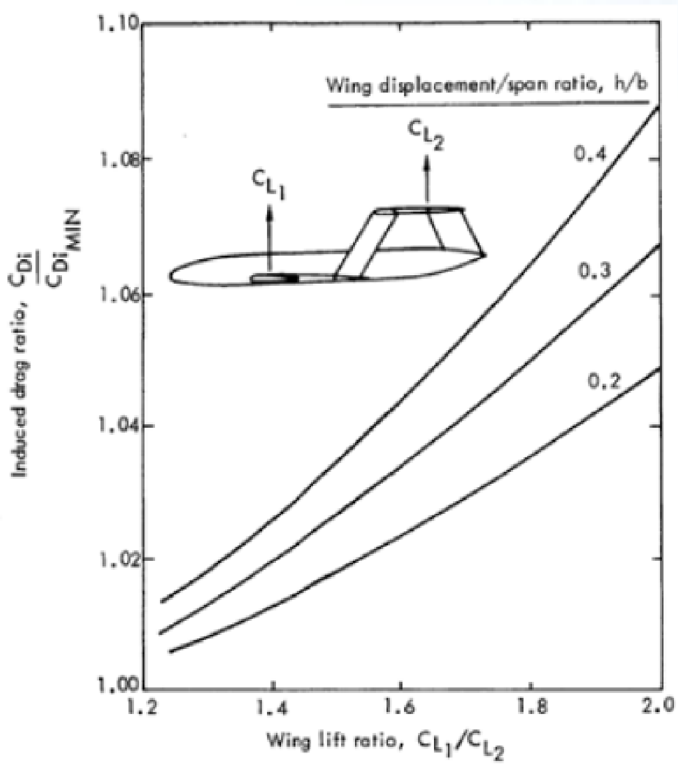
Box Wing Aircraft: Aerodynamics

Prandtl (for h/b = infinity):

$$\frac{C_{D,i}}{C_{D,i,min}} = \frac{2\,(x^2+1)}{(x+1)^2} \quad with \quad x = \frac{C_{L,1}}{C_{L,2}}$$



LOCKHEED: Transonic Biplane Concepts.
NACA CR 132462, 1974

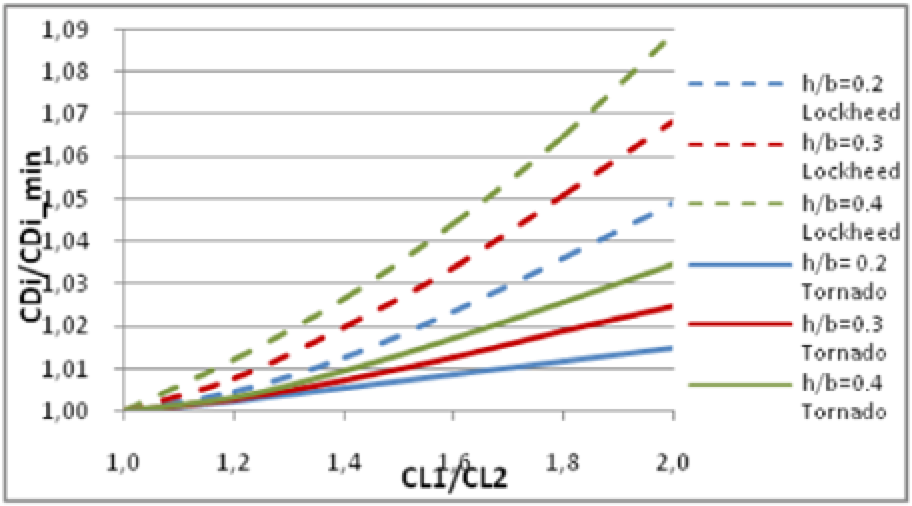


Lockheed 1974

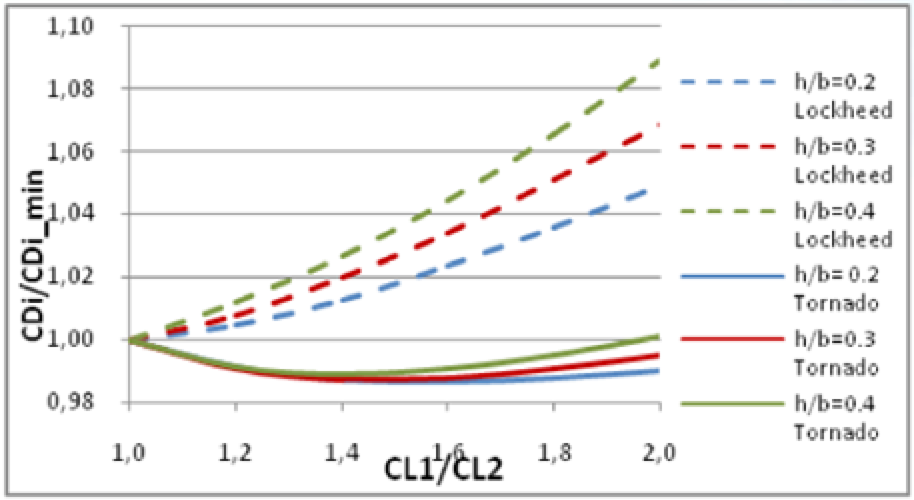
Induced drag increases if lift coefficients are different

Box Wing Aircraft: Aerodynamics

Ricardo Caja Calleja (HAW Hamburg)

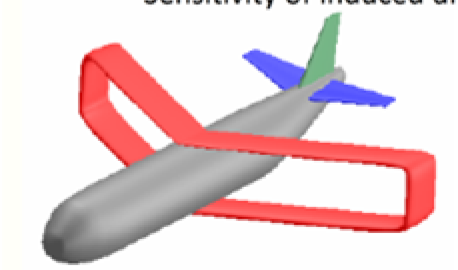


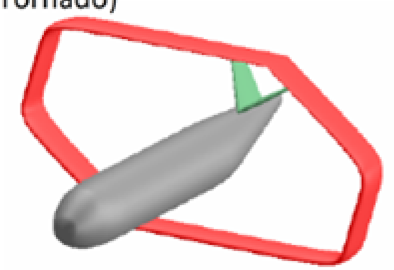
Stagger = 0



Stagger = -0.5b

Sensitivity of induced drag to non-optimum lift distributions (Tornado)





If forward wing is low wing: no drag increase

Summary

Summary

- Common for passenger aircraft is a Box Wing Aircraft (BWA) with negative stagger: The forward wing is the low wing. As such the aft wing can use the vertical tail structure for highest h/b ratio.

- This configuration could use slight positive decalage (more angle of attack on the upper wing) to adapt the upper wing to the downwash from the front wing.
- However: Positive decalage can lead to separation already at lower angle of attack and hence reduced maximum lift coefficient. A conservative design should do without decalage.

- An unequal lift share (between forward and aft wing) – as required by static longitudinal stability – does not necessarily lead to increased induced drag at (typical) negative stagger.

- Wind tunnel measurements and Vortex Lattice Method (VLM) calculations lead to a proposal of "k-values" for the "box wing equation" not far from Prandtl's results. This is straight advice to calculate induced drag of box wings for the conceptual aircraft design phase.

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